Ground state capture in ^{14}N(p,γ)^{15}O studied above the 259 keV resonance at LUNA

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Abstract. We report on a new measurement of ^{14}N(p,γ)^{15}O for the ground state capture transition at $E_p = 360$, 380 and 400 keV, using the 400 kV LUNA accelerator. The true coincidence summing effect –the major source of error in the ground state capture determination– has been significantly reduced by using a Clover–type gamma detector.

1. Introduction

The ^{14}N(p,γ)^{15}O reaction ($Q = 7297$ keV) is the slowest process in the hydrogen burning CNO cycle [1] and thus of high astrophysical interest. This reaction plays a role for the neutrino spectrum of the Sun [2] as well as in the age determination of globular clusters [3]. The reaction was recently studied in three experiments at energies ranging from $E_{cm} = 70$ to 480 keV [4–6] and before over a wide range of energies, i.e. 240 to 3300 keV ([7] and references therein). A significant reduction of the ground state contribution [8] has been found [4, 5]. However, the analysis was hampered by the fact that the usage of large detectors in close geometry has as a consequence
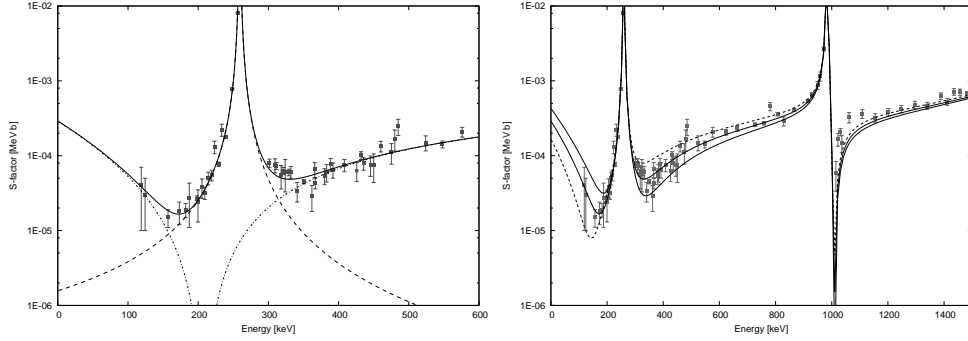
Figure 1. Astrophysical S–factor for radiative proton capture to the ground state of ^{15}O as a function of center of mass energy. The left panel shows data from [4, 5, 7] together with a previous R–matrix fit [4]. Shown is also the contribution from the 259 keV resonance alone (dashed line) and the contribution primarily from the subthreshold state and the external contribution (dot–dashed line). The right panel illustrates the influence of change in Γ_γ of the subthreshold state where Γ_γ ranges from 0.6 (dashed line), 0.8 (solid line) to 1 eV (solid thin line).

that the "ground state contribution" is masked by summing–in due to coincidence events from the cascade transitions in ^{15}O. Necessary corrections were of the order of a factor two to four, thereby increasing the uncertainty [4, 5]. Moreover, an R–matrix analysis revealed (figure 1, left panel) that below the 259 keV resonance the data followed primarily the low energy wing of the resonance. These data could not probe the behavior of the interference structure, which is needed for reliable extrapolation, due to a minimum of the S–factor curve near $E_{cm} = 160$ keV.

The total S–factor at 70 keV is known with $S(70) = 1.74\pm0.14$ keV b statistical error [6]. However, the ground state contribution at that energy is expected to be [4] $S_{gs}(70) = 0.07$ keV b, so the summing crystal study in Ref. [6] is not sufficiently sensitive to probe the contribution of the ground state transition. The value of $S_{gs}(0)$ depends on the Γ_γ of the subthreshold state at 6.79 MeV excitation energy in ^{15}O. The influence of a change in Γ_γ of the subthreshold state is illustrated in the right panel of figure 1 where Γ_γ ranges from 0.6 (dashed line), 0.8 (solid line) to 1 eV (solid thin line). When lowering the width of the subthreshold state $S_{gs}(0)$ decreases, the destructive interference minimum moves to lower energies and hence recovers much earlier at higher energies, i.e. the cross section is expected to be larger at energies above the 259 keV resonance. For the above range in Γ_γ one expects a change in cross section of a factor of three around 330 keV. Also from figure 1 it is obvious that the non–resonant shape could be studied again above $E_{cm} = 300$ keV. We have therefore designed an experiment in the energy range 300 to 400 keV using a BGO shielded Clover detector [9] to reduce significantly the summing–in contributions from the true coincidence events from the ^{15}O cascade transitions.

2. Experiment

The set up was similar to Ref. [4] with the detector placed at 55° with respect to the beam axis. The 400 kV LUNA 2 accelerator [10] provided proton beam currents of up to 350 μA on target. The N–targets were produced by reactive plasma deposition of TiN onto Ta backings with observed energy loss of 50 keV for protons at $E_p = 280$ keV

in the TiN layer. A BGO shielded Clover detector [9] with the crystals front faces at a distance of 9 cm from the target was used in the present experiment in a simplified way. The individual events of the four segments of the clover were collected in single ADC's. In addition, the analogue signals of the individual segments were summed (hard sum) and stored in another independent ADC which was in anti–coincidence with the surrounding BGO crystals for normal running conditions. While the sum of the individual segments after calibration and gain matching (soft sum) should provide the greatest reduction in the summing effect, the hard sum acts like a large crystal (at 9 cm distance as opposed to 1.5 cm [4] and 0.9 cm [5]) with Compton background reduction due to the BGO anti–coincidence circuit and reduction in the summing by the larger distance. Measurements with radioactive sources (^{137}Cs, ^{60}Co) placed at the target position, have been performed to gain absolute efficiency information. Losses due to the cascade structure of the gamma events through the anti–coincidence circuit with the surrounding BGO's have been studied in the same manner, showing less than 5% effect. This has been corrected for in the data analysis.

2.1. Target profile

The target profile was expected to deteriorate after heavy bombardment with protons. Therefore the profile was checked every day (after about 25 C proton irradiation) by a scan of the 278 keV resonance. There has been no significant change of the observed resonance energy, hence no relevant C–build up was noted during the whole course of the experiment due to an LN$_2$ cooled shroud placed before the target. One can, however, observe the following important parameter changes: i) the thickness of the target reduces with time; ii) the rear tail width increases; and iii) the integral over the target decreases. The thickness, tail-width and integral over the profile behaved nearly linearly with the total accumulated dose on the target and have been corrected for in the analysis. After at most 40% reduction in the thickness, the target was replaced.

2.2. Efficiency determination and summing corrections

Absolute and relative efficiency of the Clover detector were determined by source measurements and the γ–rays coming from the 259 keV resonance in ^{14}N(p,γ)^{15}O, respectively. Here, the branching ratios and $\omega\gamma$ value of the 259 keV resonance were used [4, 6]. A free parameter was the stoichiometry y/x of the Ti$_x$N$_y$ target. The ratios of the primary and secondary transitions were normalized to the source results and thus extending the range of energies from 662 to 6791 keV. As expected, the ground state transition showed sizable summing contributions in the hard sum spectra (figure 2). The effect is, however, much lower than the factor 3.5 [4] or even higher [5] observed in previous work at low energy. This effect was again reduced in the soft sum efficiency (fig. 2). The summing correction for the energy range of the present experiment (i.e. well above the resonance) is expected to be less then 20% for the hard sum and less then 5% for the soft sum, taking into account the previous cross section results for the ground state transition and the transitions through 6.18 and 6.79 MeV state. Hence, even an uncertainty of 10% in that correction would lead to less than 2% error in the final result. Finally, the summing–out effects for the cascade transitions (e.g. the 6.79 MeV γ–ray) can be estimated to be also less than 2% for the hard sum.
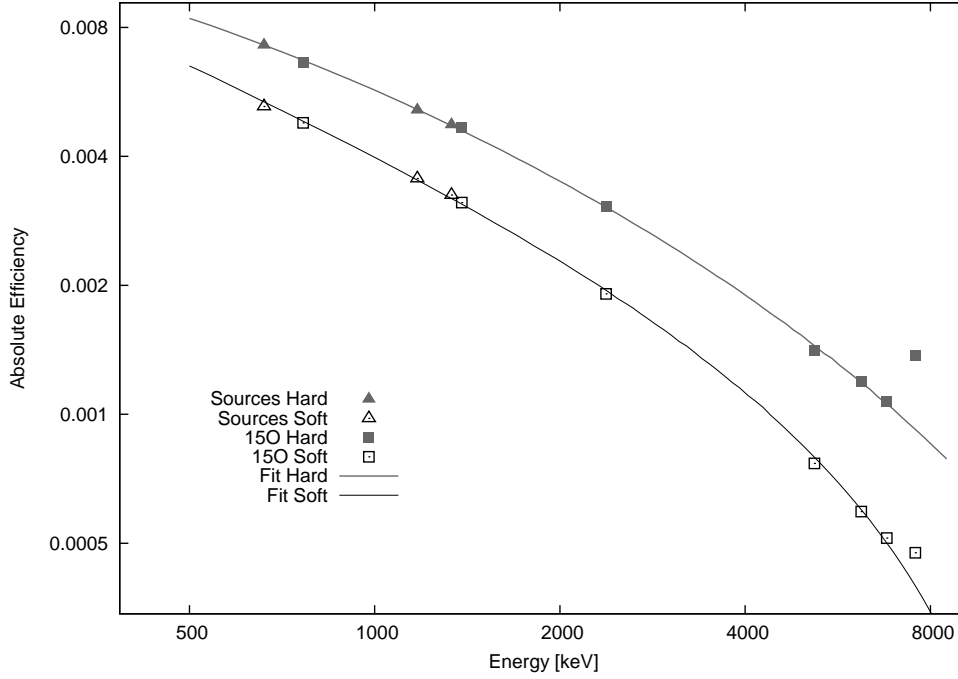
Figure 2. Absolute efficiency curves for both hard sum (upper points) and soft sum (lower points): please note the difference caused by the summing effect at $E_\gamma = 7.6$ MeV.

2.3. Relative determination of the ground state S–factor

The aim of the present experiment was to determine the cross section at energies above the 259 keV resonance (fig. 1). We determined the cross section relative to the well studied transition to the 6.79 MeV state. Such a procedure has several advantages:

- The measurement is independent of the knowledge of absolute quantities such as target stoichiometry, target profile, charge, stopping power and absolute efficiency.

- The mean value of cross section for capture to the 6.79 MeV state of recent publications [4, 5] agrees within 2%, hence no large uncertainty arise from such normalisation.

- The effective energy determination is not critical due to similar energy dependence of both cross sections which are controlled by the penetrability.

- The relative efficiency determination is not affected by large systematic errors when studying the secondary transition, the 6.79 MeV γ–line which is near the expected ground state transition.

The peak contents were obtained by subtracting a fitted linear background in the region surrounding the peak of interest. Effective energies were obtained by determining the centroid of the observed non resonant ground state transition. The resonance contribution through the tail of the target profile can be subtracted by extracting the resonance part from the 765 keV primary line and correcting for the respective efficiency. A cross check of the validity of this procedure is the comparison
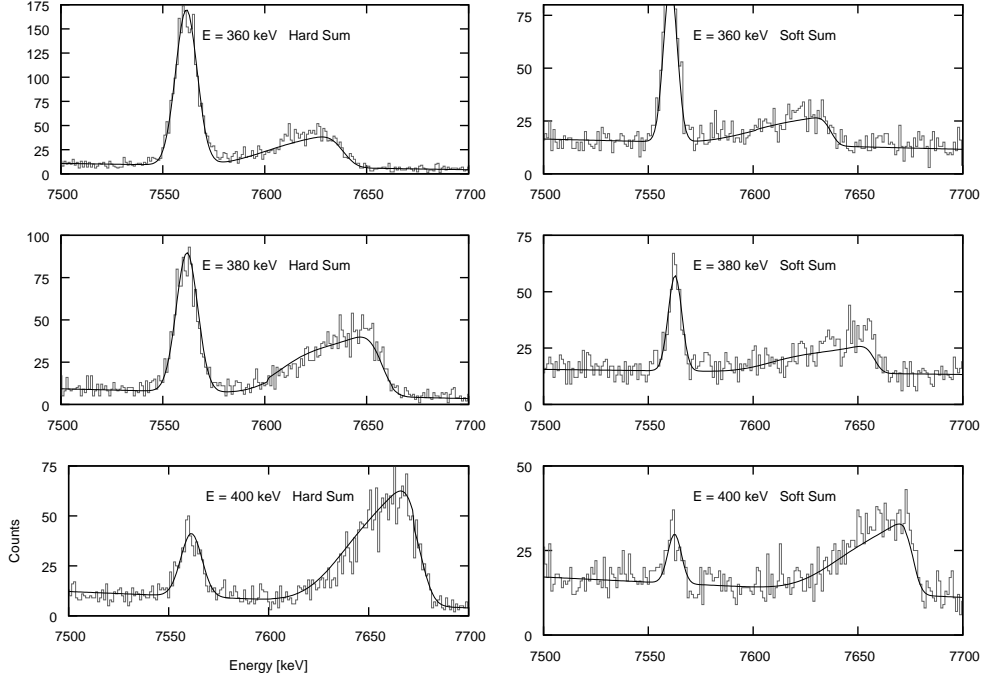
Figure 3. Line shape analysis result for all energies; left is shown the hard sum results and right the soft sum results.

of the efficiency corrected yield in the 6.79 MeV peak with the sum of the 776 keV resonant and non resonant part (shifting with proton energy). Good agreement was found after subtraction of background lines in the broad non resonant part of the primary line. This indicates that no problem arises due to incorrect angular position for the detector set up with respect to the beam axis.

2.4. Line shape analysis

In addition, the cross section can be determined independently through a line shape analysis (fig. 3). The shape of the non resonant reaction γ–lines contains information on the cross section behavior over the target thickness. As an approximation, second order polynomial function of the previous R–matrix analysis [4] was sufficient to describe the energy dependence of the cross section in the energy region studied here, i.e. $E_{cm} = 300$ to 370 keV. This function has been folded with the obtained target profiles and convoluted with a Gaussian function in order to include the detector resolution. The cross section behavior should be the same in all resulting spectra, hard and soft sum at the three energies $E_p = 360$, 380 and 400 keV. Therefore, all spectra were fitted simultaneously using the three polynomial coefficients as free parameters. The background was assumed to behave linearly and the Gaussian peak at the resonance energy was also fitted to obtain the widths for the Gaussian convolution. The overall reduced χ^2 was 1.15.
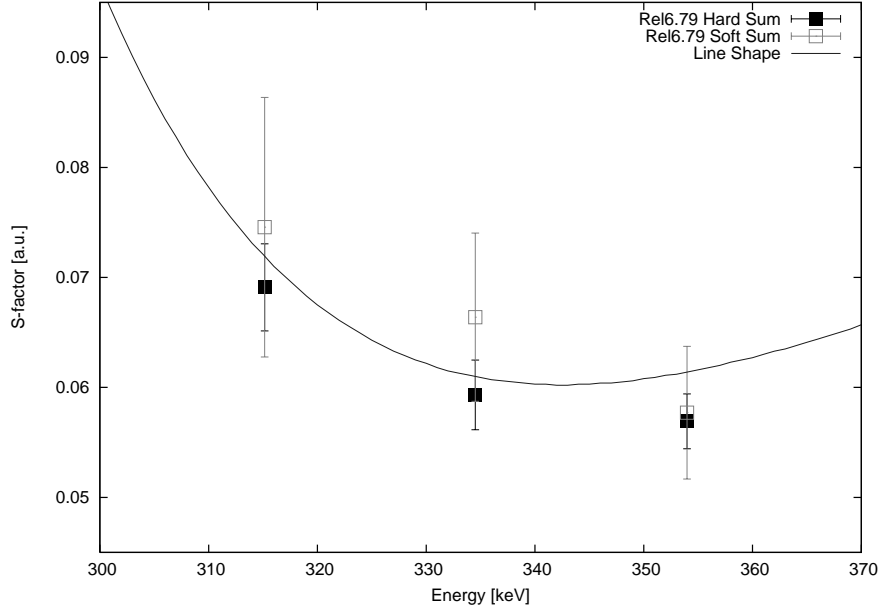
Figure 4. Preliminary results in arbitrary units for the relative analysis method (hard sum, soft sum) and the line shape analysis (see text for details).

Figure 4 shows the astrophysical S–factor in arbitrary units, obtained from different relative analysis. The results for both the hardware and software sum relative to the 6.79 MeV transition are shown together with the results of the shape analysis. The agreement is remarkable considering the fact that only the efficiency is the common parameter based on the fitted stoichiometry. This shows that the analysis methods described above are reliable.

Acknowledgments

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